Observations on the Presumed LET Dependence of SEGR

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Abstract - Single-event gate rupture (SEGR) in vertical power MOSFETs is induced by charge deposited in the epitaxial region (below the gate oxide) in concert with the weakening of the oxide, both are a result of the ion passage. Experimental and numerical results are presented comparing ions having different ranges and non-uniform LET in the device epi layer. These results indicate that the total ionization charge generated in the epitaxial layer plays a more fundamental role in causing SEGR than does incident LET, although charge deposition nearer the oxide is more important than deeper ionization. While charge deposition in the epi layer may explain the development of the electric field transient, a fuller understanding of the ion-induced dielectric weakening is needed to fully explain the SEGR results.

I. Introduction - Current understanding of the SEGR mechanism is not yet on a firm theoretical foundation. Most previous studies assume that, given a particular device, the incident LET of the impinging ion is the fundamental parameter causing SEGR. For example, the semi-empirical expression for critical SEGR voltages developed in reference 1 is of the form $V_{GS} = F \cdot V_{DS} + G$, where both F and G are functions of incident LET only. Later work [2] by the same authors and their colleagues recognized that integrating LET over the epi thickness yields a parameter more correlated with SEGR than incident LET is. Note, however, that to date they have not yet re-formulated their semi-empirical expression to incorporate this result. The impetus for the present experimental and numerical study was to explore the role of LET, beam energy, and range on SEGR susceptibility. The methodology adopted was to select ions and incident LETs with the wide differences in SEGR response so that key physical parameter(s) driving SEGR could be identified. These results serve to reinforce and extend the conclusions of reference 2.

II. Numerical Results - The effects of long-range versus short-range ion tracks on the electric field transient were studied with computer simulation using PISCES. The baseline case is an ion track of 40μm long with a constant LET of 40MeV-cm^2-mg^{-1} with a gaussian radial distribution having a 0.5μm characteristic radius. The length of the short track is 8μm (42% of the 19μm epitaxial depth) and with the same LET as the baseline case. The 19μm epitaxial layer of the simulated device has a doping level of 1×10^{16} atoms per cm^3. Doping for the substrate is 3×10^{15} atoms per cm^3 and a depth of 21μm. Figure 1 shows the results of the PISCES simulation. Note the peak electric field for the baseline case is 13.6MV/cm and for the short-range case it is 12.1MV/cm, a difference of only 11%. Reliability physics studies of TDDB (time dependent dielectric breakdown) show a very strong electric field dependence for dielectric breakdown [3], so this is probably a fairly significant difference for SEGR. This example shows, first, that when everything else is the same, ion range is an important determinant in causing SEGR, and second, that segments of ion track nearer the oxide are more important than those further away. Theoretical work is underway to identify an appropriate charge weighting function as a function of deposition depth.

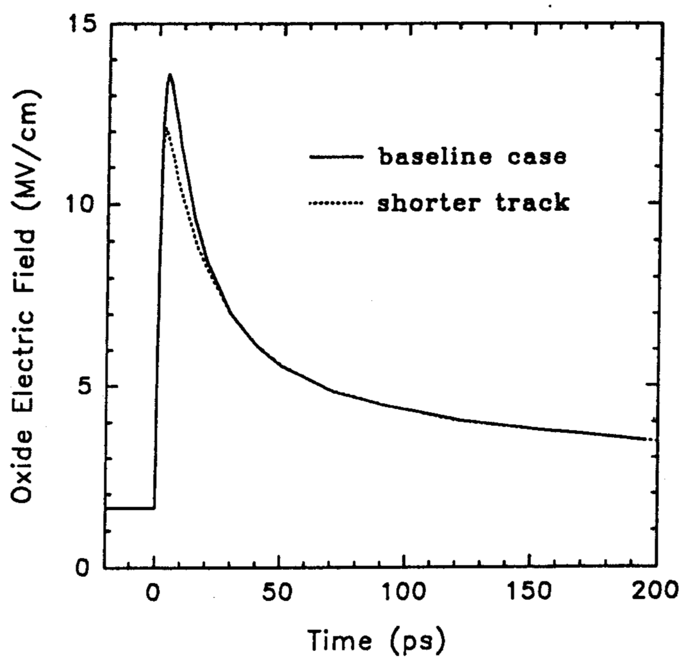

Figure 1. Comparison of the ion-induced electric field transients produced by short- (8μm) and long-(40μm) range ions (LET=40) in a device with 19μm epi layer.

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III. Description of the Test Device and Ions Used. - A non-radiation hard n-type device, the IR2N6790 manufactured by International Rectifier, with a voltage rating of 200V was selected as the test device. Oxide thickness for this device was measured to be 75 ± 5nm with an epitaxial depth of 26μm and a corresponding doping level of 1×10^{15} atoms per cm^3. Over 60 devices were tested destructively. Many of the DUTs were broken electrically, i.e. without irradiation, to establish the functional domain of the device. This data, shown in figure 2, encloses a rectangular bias space. Breakdown voltage for the IR2N6790 is consistently 245V, regardless of gate to source voltage (V_{GS}). The gate oxide ruptures at –86V independent of drain to source voltage (V_{DS}).

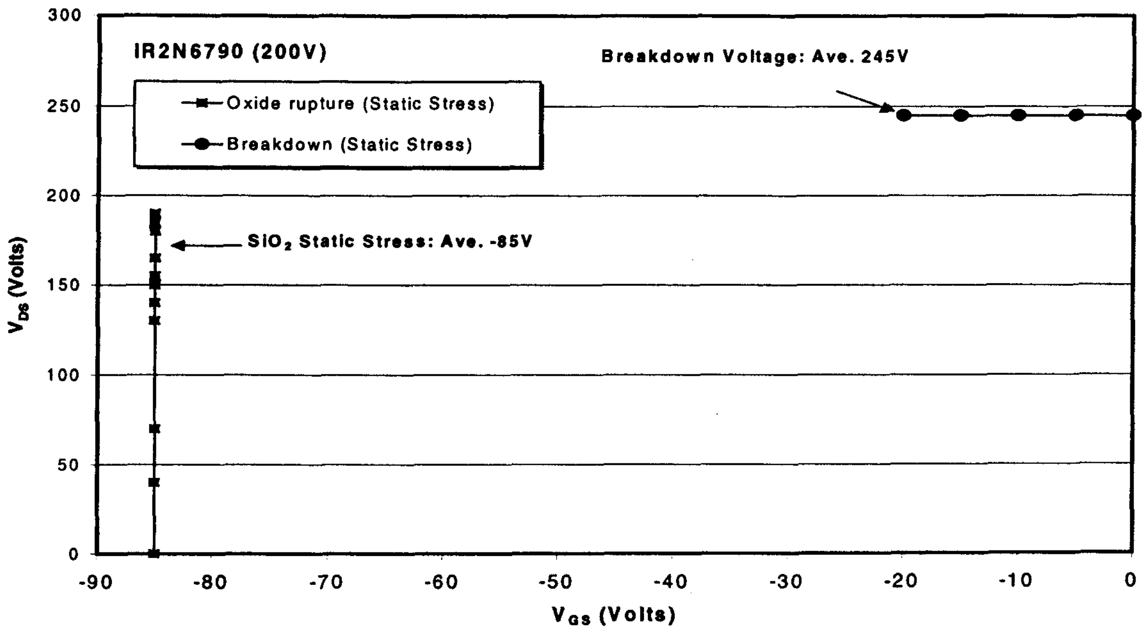
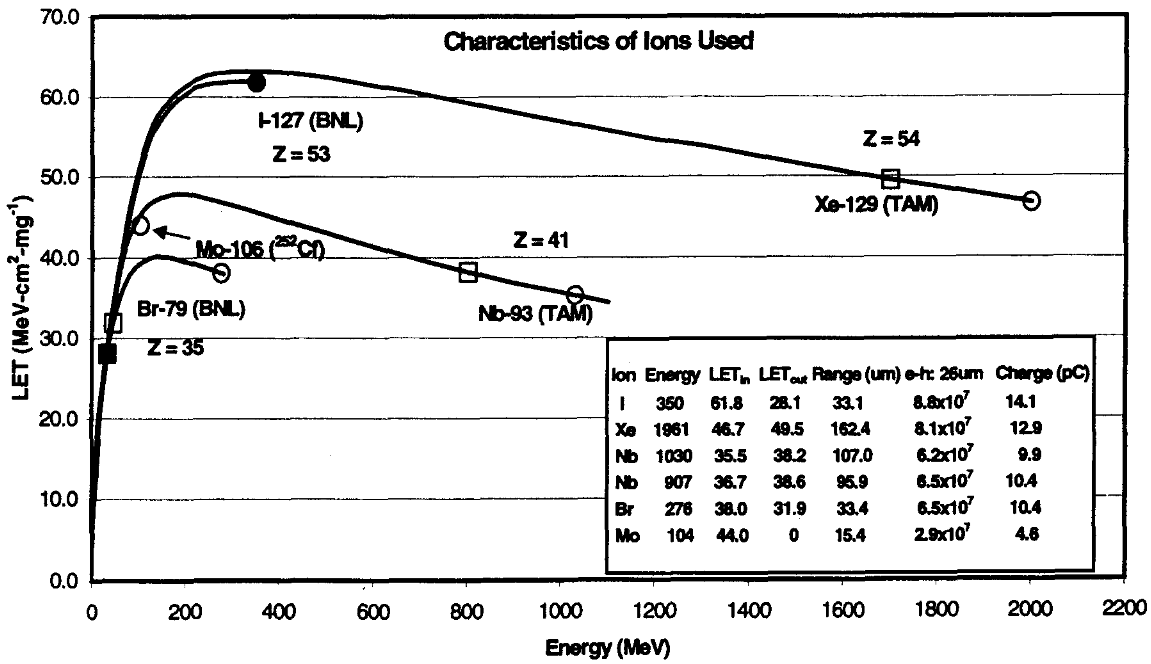


Figure 2. Measured electrical breakdown characteristics of the IR2N6790 (200V) test vehicle. Note that both the oxide and source-drain breakdowns are remarkably consistent and independent of the other bias.



Ion	Energy	LET_{in}	LET_{out}	Range (um)	e-h: 26um	Charge (pC)
I	350	61.8	28.1	33.1	8.8×10^7	14.1
Xe	1961	46.7	49.5	162.4	8.1×10^7	12.9
Nb	1030	35.5	38.2	107.0	6.2×10^7	9.9
Nb	907	36.7	38.6	95.9	6.5×10^7	10.4
Br	276	38.0	31.9	33.4	6.5×10^7	10.4
Mo	104	44.0	0	15.4	2.9×10^7	4.6

Figure 3. TRIM results for the ions used. Incident LETs are denoted by circles and LETs exiting the epi by squares.

Figure 3 shows curves for LET as a function of ion energy for the ion beams used in this study as given by TRIM. Note the peak LET values increase with Z, as systematized by Ziegler's formulation. Three long-range ions accelerated by the Texas A&M University (TAM) cyclotron were used: 1961MeV xenon (Xe^{129}) and 1030MeV & 907MeV niobium (Nb^{93}). Two intermediate range ions, 350 MeV iodine (I^{127}) and 276 MeV bromine (Br^{79}), were selected from experiments conducted at Brookhaven National Laboratory (BNL). In order to supplement the ion beam data set with short-range ions, fission fragments spontaneously emitted from a Californium (Cf^{252}) source were used. Molybdenum (Mo^{104}) is used here as representative of those ions because it is the most abundant of the lighter and more energetic half of the distribution of fragments (which are presumed to be more effective at causing SEGR).

IV. Experimental Results - The results obtained are given in figure 4 as contours of the minimum V_{DS}-V_{GS} bias conditions under which SEGR occurs for the selected ions. While the statistics of each condition are admittedly low, there are some unexpected, but reproducible characteristics. In particular, some of the curves

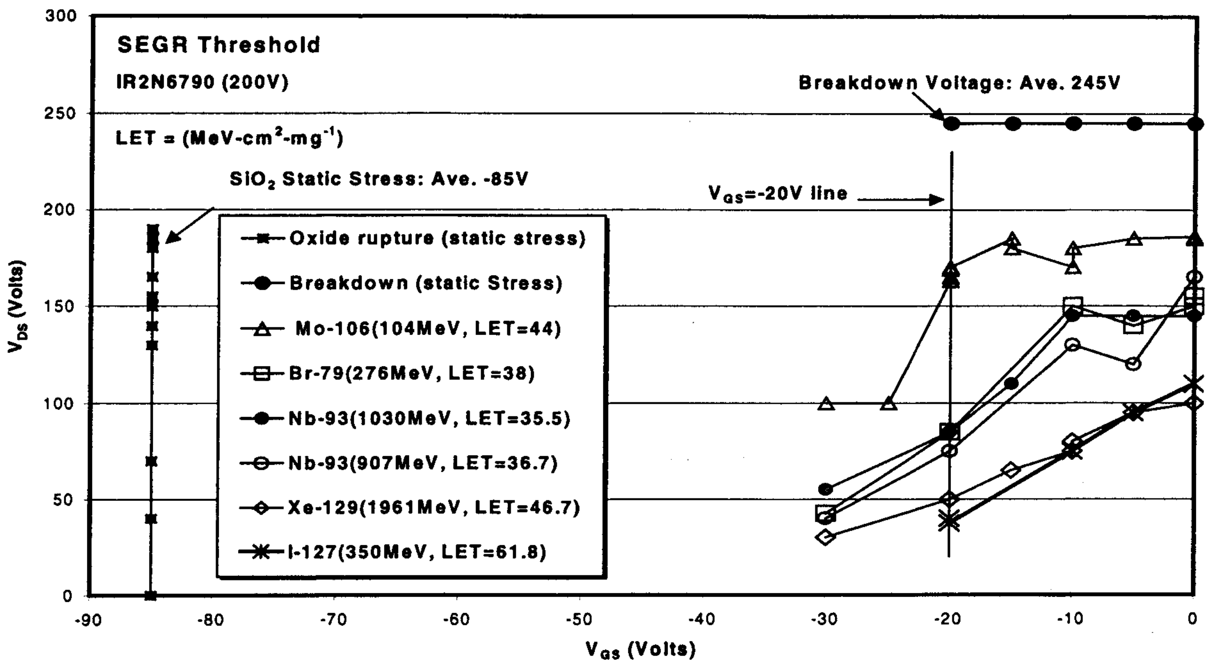


Figure 4. Experimental contours of minimum bias points for causing SEGR in the V_{DS}-V_{GS} operational domain for six selected ion beams.

deviate significantly from fitting straight lines and, in some instances, they cross; the simple LET dependence of reference 1 is clearly violated. This can also be clearly seen in comparing the Xe^{129} and I^{127} curves where the ability to cause SEGR is similar, but the LETs (47 and 62) are quite different.

V. Discussion - To simplify the following analysis, the test device overlayers are ignored. Additionally, the capacity of an ion to cause SEGR is somewhat arbitrarily quantified using the minimum V_{DS} values for SEGR at V_{GS} = −20V. These are normalized to the measured breakdown voltage, yielding a fraction which is subtracted from one. The result is a convenient number between zero and one for "SEGR capability." For example, 350MeV I^{127} , the ion in these experiments most capable of causing SEGR, has a value of ~0.8 while 104MeV Mo^{106}, the least capable ion, is ~0.3 .

Plotting SEGR capability versus incident LET yields a complicated figure where SEGR capability is not a single-valued function of LET, as can be seen in figure 5(a). On the other hand, plotting SEGR capability versus charge deposition yields a fairly linear dependence; see figure 5(b). We conclude that epi-deposited charge (even though not properly weighted) is a more fundamental cause of SEGR than is incident LET. This conclusion derived from experimental points on five Bragg curves agrees with a similar conclusion on epi-deposited energy in reference 2 that is based on a similar number of data points on essentially one stopping curve. Note that deposited charge and deposited energy are proportional over most of the ion range so the two conclusions are equivalent. The common key to obtaining this conclusion is apparently including an ion that starts after the energy loss peak, i.e., on the declining part of the Bragg curve.

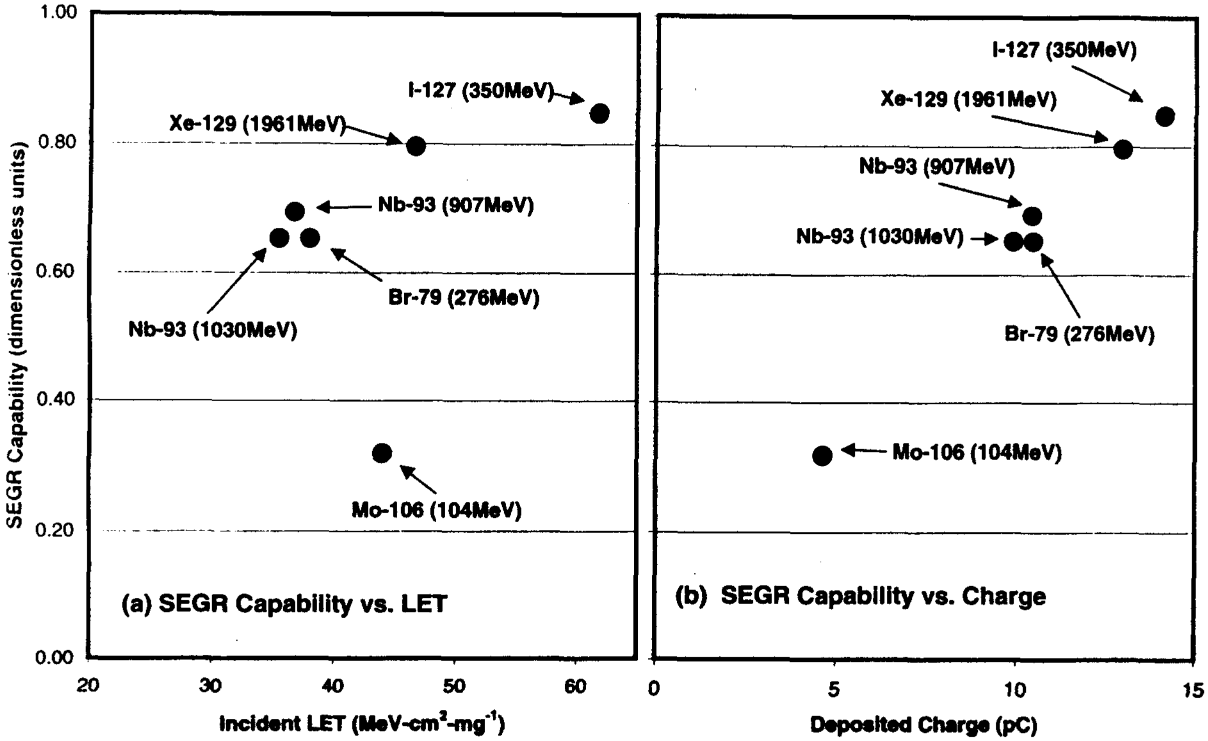


Figure 5. Comparison of SEGR susceptibility of the IR2N6790 at V_{GS}=-20 plotted (a) as a "function" of incident LET and (b) as a function of deposited charge in the epi. Clearly the latter shows a more linear trend.

However, even 5(b) does not fix the "kink" around the three middle ions. 276MeV Br^{79} has the roughly the same ability to cause SEGR as the higher energy (lower incident LET) Nb^{93} which causes less ionization in the epi. The *lower* energy Nb^{93} deposits roughly the same charge in the epi, but causes SEGR more effectively. The likely explanation lies in the oxide weakening effect of the ion passage: the higher energy niobium is more effective at reducing the oxide's breaking point while the lower energy niobium weakens the oxide more than the bromine beam. Experimental and theoretical investigations of the effect of the ion passage on the oxide in power MOSFETs, as well as MOS capacitors, is a continuing effort at several labs including JPL. Hopefully, this work will be fruitful. Note that early work by Wrobel on this problem [4] assumed a fundamental dependence on LET but couldn't discriminate between two proposed functional forms: "The oxide data fits either a linear or square root response…" [4, p. 1265]

VI. Conclusions - SEGR is a phenomenon driven by charge deposition and oxide weakening, both of which are induced by the passage of an energetic heavy ion. In particular, the short-range ions can produce SEGR even though their ranges are not enough to exit the epitaxial layer. Neither incident LET nor any other beam parameter considered so far (i.e., incident energy, momentum, impact diameter, delta ray energy) is as fundamental in causing SEGR as total charge deposition in the epitaxial layer. Although the correlation between SEGR capability and total deposited charge is good, potential improvements are currently being pursued using a physical weighting function of charge deposition position. Additionally, work on the direct effects on the oxide of the ion passage is being done.

VII. References -

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